# MAPS OF THE MOLECULAR EMISSION AROUND 18 EVOLVED STARS

K. Z. Stanek[1] and G. R. Knapp

Princeton University Observatory, Princeton, NJ 08544-1001
e-mail: stanek@astro.princeton.edu, gk@astro.princeton.edu

K. Young and T. G. Phillips

CSO, California Institute of Technology, Pasadena, CA 91125
e-mail: rtm@tacos.caltech.edu, phillips@tacos.caltech.edu

## ABSTRACT

We present maps at $20''$ resolution of the molecular emission around 18 evolved stars (14 asymptotic giant branch stars, one supergiant, two proto-planetary nebulae and one planetary nebula), mostly in the $^{12}CO$(3-2) line. Almost all molecular envelopes appear to be at least marginally resolved at this resolution. A substantial fraction of the molecular envelopes show clear deviations from spherical symmetry in the form of elliptical or bipolar envelopes. This indicates that there is a need to implement non-spherical mass loss in current scenarios of the late stages of stellar evolution, in particular on the asymptotic giant branch.

*Subject headings:* stars: mass loss – stars: late-type – stars: circumstellar shells – nebulae: structure

## 1.   Introduction

Stars in the latest stages of evolution, i.e. asymptotic giant branch (AGB) and red supergiant stars, lose mass in the form of cool dusty molecular winds at speeds of typically 5 to 40 $km\ s^{-1}$. The amounts of mass lost (up to $10^{-4}\ M_\odot\ yr^{-1}$) and the duration of the mass loss phase (about $10^5$ years) are large enough to ensure that this process dominates

---

[1]On leave from N. Copernicus Astronomical Center, Bartycka 18, Warszawa 00-716, Poland

the evolution of the star at this stage. Molecular line emission and dust continuum emission can both be observed from these envelopes, and the use of these probes to measure mass loss has become a well-developed and active field in the past fifteen years. Work has been directed towards such questions as measuring the rate of mass loss and its effect on the evolution of the star, the gas to dust ratio, the composition of the envelope (including the effects of photochemistry) and the rate of mass return to the interstellar medium. The models used to analyze the observations usually contain the assumption that mass is lost isotropically at a constant rate and at a constant outflow speed. Observations with the new interferometers and submillimeter telescopes have shown, however, that these assumptions are too simplistic. Highly evolved envelopes, such as that surrounding CRL618, show pronounced bipolar structure and sometimes have a second very high-velocity wind close to the star (Cernicharo et al. 1989; Gammie et al. 1989). Observations of CRL 2688 (Young et al. 1992) show the presence of two fast winds, one with an outflow speed of 45 $km\ s^{-1}$ and a second with a speed of at least 100 $km\ s^{-1}$. It is unlikely that these fast winds are driven by radiation pressure – the momentum in the starlight is insufficient.

Here we present observations showing that the assumptions involving isotropy of the mass loss are also simplified. For 18 stars at late evolutionary stages we mapped the molecular envelopes, mostly in the CO(3-2) line. Examining the CO(3-2) line, rather than a lower $J$ transition, offers several advantages. The first is that higher $J$ transitions have higher critical densities for collisional excitation. For this reason emission from molecular clouds is less extensive and the observations are less apt to be contaminated by Galactic emission. Second, the antenna temperature of the CO(3-2) line will in general be higher than in the lower $J$ lines. While the rotational transitions above 3-2 may have even higher brightness temperatures, the Earths atmosphere is much less transparent at high frequencies.

## 2. Observations

The data were obtained in January 1990 (R Scl, o Cet, U Cam, VY CMa, OH 231.8, RS Cnc, R Leo, IRC +10216), April–May 1990 (R Leo, V Hya, RT Vir, W Hya, R Cyg, CRL 2688, R Cas), June and August 1992 (M 57) and September 1993 ($\chi$ Cyg, V Cyg, IRC +40540, U Cam), using the 10.4-m Caltech Submillimeter Observatory (CSO) telescope at Mauna Kea (Hawaii, USA). We mostly observed the $^{12}$CO(3-2) line at $\nu_o = 345.796$ GHz, with a FWHM beam of 20$''$ and a main-beam efficiency of 60%. The receiver was a double sideband SIS detector with a temperature of about 200 K and the zenith optical

depth was 0.1 to 0.2, giving effective single-sideband system temperatures of about 700 K for observations made at elevations above 50 degrees. The spectral line backend was a 1024 channel acousto-optical spectrograph (AOS) of bandwidth 500 MHz, giving a channel spacing of 0.43 $km\ s^{-1}$ and a velocity resolution of 0.8 $km\ s^{-1}$. The receiver detects both sidebands, and in some of the observations the emission from other spectral lines is detectable and strong enough to allow mapping also in these lines. The CS(7–6) line at $\nu_o = 342.883$ GHz is detected in the carbon stars IRC 10216, CRL 2688 and V Cyg. The $^{29}$SiO(8-7) line at $\nu_o = 342.9791$ GHz is seen from the oxygen stars R Leo and W Hya.

The individual observations were calibrated and those with bad (strongly curved) baselines or high r.m.s. noise levels were rejected. The individual observations were then averaged, weighted appropriately by the r.m.s. noise, and a first or second order polynomial baseline was removed from the spectrum by fitting it to regions of the spectrum judged to be free of line emission. The data for the first and last fifty or so channels of the 1024 channel AOS used at CSO were noisy and were not used in the fit.

Pointing was found to be correct within 5″, but for some stars uncertainties in the catalog position resulted in the shift of the observed position of maximum flux. For maps which are the result of averaging over several individual maps, the telescope pointing was checked before each map was made.

## 3.   Results

Some characteristics of the mapped stars are presented in Table 1. We observed 14 AGB stars, one supergiant star (SG), two protoplaneteary nebulae (PPNe) and one planetary nebula (PN). Spectral and variability types were obtained using the SIMBAD database. Coordinates and chemical types were taken from the overview of CO observations by Loup et al. (1993).

In Table 2 we present the observational properties of the stars' molecular emission, determined by analysis of the line profile observed at the central position (with the exception of M57 - see the notes to Table 2). Because we usually obtained about 10 central position observations for each star, the resulting spectra have high signal-to-noise ratios. As may be seen in the maps we present in Figures 2–19, the central positions do not always coincide with the observed maximum of the line intensities, so we give the flux and line intensity taken from the position at which the flux is highest.

To obtain the LSR velocity of the star $v_{lsr}$, its expansion velocity $v_e$ and some measure

Table 1.   Observed Stars

| Name | Other name | Coordinates (1950) | | Spe. type | Class | Chem. type |
|---|---|---|---|---|---|---|
| | | $\alpha$ (h m s) | $\delta$ (° ' ") | | | |
| R Scl | IRC −30015 | 01 24 40.02 | −32 48 06.8 | C6II | SRa | C |
| o Cet | Mira | 02 16 49.11 | −03 12 22.4 | M7IIIe | Mira | O |
| U Cam | IRC +60124 | 03 37 29.09 | +62 29 18.8 | C6 | SRb | C |
| VY CMa | IRC −30087 | 07 20 54.74 | −25 40 12.3 | M3-4II | SG(Lc) | O |
| OH 231.8+4.2 | QX Pup | 07 39 58.90 | −14 35 44.0 | M6I-M9III | PPN | O |
| RS Cnc | IRC +30209 | 09 07 37.80 | +31 10 05.0 | M6IIIase | SRc | O |
| R Leo | IRC +10215 | 09 44 52.24 | +11 39 40.4 | M8IIIe | Mira | O |
| IRC +10216 | CW Leo | 09 45 14.89 | +13 30 40.8 | Ce | Mira | C |
| V Hya | IRC −20218 | 10 51 37.27 | −21 15 01.1 | C9I | SRa | C |
| RT Vir | IRC +10262 | 13 00 05.87 | +05 27 15.0 | M8III | SRb | O |
| W Hya | IRC −30207 | 13 46 12.08 | −28 07 08.8 | M8e | SRa | O |
| M57 | Ring Nebula | 18 51 43.70 | +32 57 56.2 | ?p | PN | ⋯ |
| R Cyg | IRC +50301 | 19 35 28.69 | +50 05 11.7 | S6e | Mira | S |
| χ Cyg | IRC +30395 | 19 48 38.53 | +32 47 09.9 | S7e | Mira | S |
| V Cyg | IRC +50338 | 20 39 41.42 | +47 57 43.2 | C6e | Mira | C |
| CRL 2688 | Egg Nebula | 21 00 19.90 | +36 29 45.0 | F5Iae | PPN | C |
| IRC +40540 | LP And | 23 32 01.30 | +43 16 27.0 | C | ⋯ | C |
| R Cas | IRC +50484 | 23 55 52.07 | +51 06 37.3 | M7IIIe | Mira | O |

Table 2.   Observational Results

| Name | $T_{max}$ [K] | Flux[A] [K km s$^{-1}$] | $V_{lsr}^{B}$ [km s$^{-1}$] | $V_e^{B}$ [km s$^{-1}$] | $\gamma^{B}$ | $V_{wing}$ [km s$^{-1}$] | $\sigma_1^{C}$ [K] | $\sigma_2^{C}$ [K] |
|---|---|---|---|---|---|---|---|---|
| R Scl | 2.4 | 58.7 | −19.0 | 15.2 | 0.1 | 19.0 | 0.08 | 0.27 |
| o Cet | 15.2 | 88.1 | 46.6 | 7.0$^{D}$ | 18$^{D}$ | 10.0 | 0.06 | 0.19 |
| U Cam | 1.5 | 45.6 | 4.9 | 24.5 | 0.4 | 29.0 | 0.04 | 0.22 |
| VY CMa | 2.6 | 159.6 | 17.6 | 32.6 | 0.4 | 92.0 | 0.06 | 0.25 |
| OH 231.8+4.2 | 1.9 | 140.8 | 32.0$^{D}$ | 65.0$^{D}$ | 11$^{D}$ | 125.0 | 0.07 | 0.19 |
| RS Cnc | 4.3 | 29.8 | 6.8 | 4.8$^{D}$ | 4.6$^{D}$ | 10.2 | 0.07 | 0.16 |
| R Leo | 2.8 | 31.1 | −0.9 | 7.9 | 2.1 | ⋯ | 0.05 | 0.15 |
| R Leo$^{E}$ | 0.6 | 3.8 | ⋯ | 6.0$^{F}$ | ⋯ | ⋯ | 0.05 | 0.15 |
| IRC+10216 | 42.0 | 906.0 | −26.2 | 14.5 | 1.5 | ⋯ | 0.19 | 0.50 |
| IRC+10216$^{G}$ | 9.1 | 189.5 | −22.9 | 14.9 | 1.7 | ⋯ | 0.19 | 0.50 |
| V Hya | 3.2 | 76.0 | −16.0$^{D}$ | 30.0$^{D}$ | 20$^{D}$ | ⋯ | 0.10 | 0.14 |
| RT Vir | 0.9 | 10.4 | 17.3 | 8.4 | 1.3 | ⋯ | 0.07 | 0.13 |
| W Hya | 2.2 | 22.6 | 40.6 | 8.5 | 1.1 | ⋯ | 0.12 | 0.25 |
| W Hya$^{E}$ | 1.2 | 8.0 | ⋯ | 7.0$^{F}$ | ⋯ | ⋯ | 0.12 | 0.25 |
| M57 | 1.5 | 28.3 | −2.0$^{F}$ | 27.0$^{F}$ | ⋯ | ⋯ | ⋯ | 0.20 |
| R Cyg | 1.3 | 14.6 | −18.2 | 10.4 | 1.9 | ⋯ | 0.17 | 0.25 |
| χ Cyg | 3.0 | 41.5 | 10.6 | 9.2 | 1.4 | 13.5 | 0.19 | 0.35 |
| V Cyg | 2.4 | 38.0 | 14.2 | 11.6 | 1.4 | ⋯ | 0.14 | 0.35 |
| V Cyg$^{G}$ | 0.8 | 11.6 | ⋯ | 12.0$^{F}$ | ⋯ | ⋯ | 0.14 | 0.35 |
| CRL 2688 | 10.0 | 288.3 | −34.8 | 23.0 | 19 | 50.0 | 0.20 | 0.25 |
| CRL 2688$^{G}$ | 1.8 | 41.4 | ⋯ | 22.0$^{F}$ | ⋯ | ⋯ | 0.20 | 0.25 |
| IRC+40540 | 2.6 | 46.7 | -16.8 | 14.6 | 1.9 | ⋯ | 0.17 | 0.35 |
| R Cas | 4.0 | 76.0 | 24.3 | 12.3 | 1.2 | 21.0 | 0.10 | 0.20 |

[A]Flux was calculated by integration over whole velocity range, i.e. with possible wings (see $V_{wing}$).

[B]Those values were obtained by fitting the line shape given by Eq.1.

[C]The two values of r.m.s. correspond to: $\sigma_1$ – r.m.s. of the weighted mean of central position spectrum; $\sigma_2$ – typical r.m.s. of the spectra used for constructing the map.

[D]Line shape is not well described by Eq.1 – fitted values should be treated only as approximations.

[E]SiO (8-7) line.

[F]No line profile was fitted – line parameters were estimated by eye.

[G]CS (7-6) line.

Note. — $T_{max}$ and flux (Columns [2] and [3]) were taken as highest values in the map (in some cases telescope was clearly mispointed). Line profile characteristics in Columns (4)-(6) were obtained using the central position r.m.s. noise weighted spectra, except M57, where average of all spectra within 100" × 100" region was used.

Fig. 1.— Map of the CO(3-2) emission from OH 231.8+4.2 (continuous line contours), along with fitted model (dotted line contours). Crosses indicate observed positions. For details see text.

of the line shape, we fitted (for most of the stars) the simple line profile proposed by Olofsson et al. (1993) and given by

$$T_A(v) = T_0 \left[ 1 - \left( \frac{v - v_{lsr}}{v_e} \right)^2 \right]^{\gamma/2} , \qquad (1)$$

where $v_{lsr}, v_e$ are defined above, $T_0$ is the line intensity at the line center, and $\gamma$ describes the line shape. The values of $0 > \gamma$, $2 \gg \gamma > 0$, $\gamma = 2$ and $\gamma \gg 2$ correspond to a horned, a rectangular, a parabolic and a gaussian-like line profile (for details see Olofsson et al. 1993 and their Fig.5). For some stars (indicated in Table 2) the fit was not satisfactory or no fit at all was attempted.

Some of the line profiles show the presence of wings, sometimes strong and very extended (for example OH 231.8+4.2 or VY CMa). The presence of wings is indicated in the $V_{wing}$ column in Table 2. Finally, the last two columns give r.m.s. noise of the central position spectrum and typical r.m.s. deviations of the spectra used for constructing the map.

In subsequent sections we describe observations of 18 observed evolved stars, in particular concentrating on the observed spatial distribution of the molecular emission.

The reality of the observed spatial features in the molecular emission depends on the signal-to-noise ratio (compare peak intensities in Table 2 with typical r.m.s. deviations of the spectra used for the map construction) of the maps, but as we observed stars with rather strong emission, in most of the cases our maps are clean and we believe the features present at the 10-20% level of the total integrated flux are real.

To estimate the real sizes of the molecular envelopes, for every star except M57 we have fitted to the data a biaxial gaussian, convolved with the telescope beam pattern. This way we obtained a FWHM extent of the underlying emission as well as the position angle of the major axis. For some of the stars, which we indicate in the description below, the fit was not good, so the values quoted should be treated only as approximate. The example of the fit to one of the observed stars, OH231.8+4.2, is shown in Fig.1.

### 3.1.   R Scl

The map of a $1' \times 1'$ region around this C-rich semi-regular variable (Fig.2) shows that the CO emission from this star is well resolved. From the fit to the total integrated flux map of CO J=3-2 emission (Fig.2, left upper corner) we get an angular extent at half maximum of $20'' \times 15''$. The fitted position angle of the major axis is $75°$. The CO J=3-2 line profile towards the star position may be described as two-peaked, corresponding to partially resolved, optically-thin emission (but the formal $\gamma$ value from Eq.1 is 0.1, and there is an enhanced blue horn).

As may be seen in Fig.2, the observed CO J=3-2 emission clearly departs from spherical symmetry, both in the form of overall, roughly east-west elongation (best seen in the integrated emission in the range $-30, -23 \ km \ s^{-1}$) and smaller size irregularities. Also, the CO J=3-2 line profile towards the star position shows significant deviations from the fitted flat-topped profile, with most noticeable the blue horn enhancement at $\sim -33 \ km \ s^{-1}$. Integrated emission between –38 and $-30 \ km \ s^{-1}$ shows signs of south-north elongation.

### 3.2.   o Cet

Fig.3 shows maps of the CO(3-2) emission for this well-known star. The emission is resolved, with an angular extent at the half maximum of about $15'' \times 13''$ and a position

Fig. 2.— Map of CO(3-2) emission from R Scl. Left upper panel shows map of the total integrated flux, with first contour at 10% of maximum flux and next contours also at every 10%, with 50% contour marked with heavy line. Other panels show the maps of flux integrated over different parts of the line, with velocity ranges showed in brackets. For those maps first contour is at 5% of the maximum of total flux, so are the next contours. Crosses indicate observed positions. The bottom panel shows the line profile toward the central star position, along with the best fit to the line shape given by Eq.1.

angle of 40°. The CO(3-2) line profile toward the star is not well described by Eq.1, so both $\gamma$ and $v_e$ depend strongly on the part of the line which is fitted.

This star is a subject of the detailed study by Knapp et al. (1994a), so here we only indicate the possibility of slight elongation in the northeast-southwest direction, and also a small north-south shift in the position of the peak intensity with velocity, showing that the blue-shifted and red-shifted emission is displaced from the central position by $\pm 4''$. This agrees with the results of the higher resolution maps of Planesas et al. (1990a,b).

### 3.3.   U Cam

Fig. 3.— As in Fig.2 for o Cet (Mira).

The total integrated flux map of the CO(3-2) emission of this star (Fig.4) has a fitted angular extent at half maximum of $16'' \times 13''$, although the fit is not a very good due to the peculiarities of the emission mentioned below. The fitted position angle of the major axis is about $20°$. The CO(3-2) line profile toward the star is best fit by flat-topped parabola ($\gamma = 0.4$). As in the case of R Scl, we can see the blue horn enhancement, but not so strongly pronounced.

The CO(3-2) maps presented in Fig.4 are quite remarkable. First, there is very clear, roughly south-north elongation, with an aspect ratio of about 2:1. But there is also a second elongation visible, roughly perpendicular to the first one, forming together a T-shaped envelope. The map of the bluemost part of the emission line ($-24, -12 \; km \; s^{-1}$) shows the presence of secondary peak, separated by about $25''$ from visible in all maps at the same position main peak.

### 3.4. VY CMa

VY CMa is the only supergiant star in our sample. Maps of the CO(3-2) emission appears to be only partially resolved, with the fitted FWHM extent of $10''$. The line profile

Fig. 4.— As in Fig.2 for U Cam.

towards the star position shows broad, strong wings. The formal fit to the central part of the line gives $\gamma = 0.4$.

The envelope seems only slightly resolved, although there is some irregular structure present, clearly visible in the map of total integrated emission. This is probably due to noise, as the maps of the emission coming from the center of the line are much cleaner than maps of the emission coming from the wings. The position of peak intensities does not change with velocity and is shifted $10''$ west from the center of the map; this apparent offset is probably not real and may be due to bad pointing.

### 3.5.   OH 231.8+4.2

Fig.6 shows maps of the CO(3-2) emission, which appears to be resolved. From the total integrated flux map of CO(3-2) emission we get an angular extent at half maximum of $15'' \times 1''$, i.e. the emission is unresolved in the direction perpendicular to the major axis. The position angle of the major axis is about $5°$. The fit to the emission is shown in Fig.1. The CO(3-2) line profile towards the star position is remarkable, with wings extending over $100\ km\ s^{-1}$. The formal fit of the line shape given by Eq.1 depends strongly on which

Fig. 5.— As in Fig.2 for VY CMa.

velocity range is used for the fit, so the formal $\gamma = 11$ only indicates the gaussian-like shape of the line, i.e. corresponds to unresolved, optically thick emission.

Maps of different parts of the line show clear bipolar structure – the peak intensity moves from the north to the south with velocity. The maximal displacement from the central position is about $\pm 8''$. The elongation clearly visible in the map of the total integrated flux seems be mainly due to this shift, but individual maps still show some north-south elongation, especially well seen in the maps of the wings . Existence of the two components in the emission, one unresolved with only moderate outflow velocities and another showing clear bipolar structure and outflow velocities greater then 100 $km\ s^{-1}$ agrees with the CO(1-0) observations by Morris et al. (1987).

### 3.6.   RS Cnc

The total integrated flux of the CO(3-2) emission of this star (Fig.7) has the fitted angular extent at half maximum of $12'' \times 8''$. The position angle of the major axis is 70°. The CO(3-2) line profile toward the star is not well described by Eq.1, but formal fit to the

Fig. 6.— As in Fig.2 for OH 231.8+4.2.

central part of the line gives $\gamma = 4.6$, i.e. the line is gaussian-like (unresolved and optically thick). This line shape is similar to that of o Cet.

As may be seen in Fig.7, the CO(3-2) maps indicate a possible slight west-east elongation, which is confirmed by the fitting procedure described earlier. There is no indication of changes in the position of peak intensity with velocity.

### 3.7. R Leo

This nearby Mira variable was mapped at $9''$ spacing and a $7 \times 7$ grid. The maps of the molecular emission are presented in Fig.8. From the map of the total integrated flux in the CO(3-2) line we get the fitted angular extent of the emission at half maximum of $14'' \times 11''$ and the position angle of the major axis $125°$. The spectrum towards the star position reveals in addition to the CO(3-2) line, a weaker SiO(8-7) line detected in the image sideband, apparently lying just bluewards of CO(3-2) line. As R Leo was mapped twice, in January 1990 ($5 \times 5$ map) and May 1990 ($7 \times 7$ map), we present here only bigger maps. We used the spectrum from January 1990 to fit a theoretical line profile as this spectrum was the result of averaging about 20 individual spectra, much more that were taken in May

Fig. 7.— As in Fig.2 for RS Cnc.

1990. The best fit was achieved with $\gamma = 2.1$, i.e. inverted parabola fit, but there is clearly visible red horn enhancement at about 3 $km\ s^{-1}$ present in spectra taken in both epochs.

As we mentioned above, molecular emission from R Leo was mapped twice, once on $5 \times 5$ grid and second time on $7 \times 7$ grid. We found good agreement between the maps taken in both epochs. First, there is clearly present southeast-northwest elongation, visible also in the map of SiO(8-7) emission. Second, there is systematic shift in the position of the peak intensities with the velocity, from west for approaching parts of the envelope to east for receding emission, what indicates a bipolar character of the emission. It is interesting to notice that the peak intensity of the SiO(8-7) emission is shifted even more to the east than the redmost part of the CO(3-2) emission.

R Leo was also mapped by Bujarrabal & Alcolea (1991, hereafter: BA), but it is rather difficult to compare our results with their smaller, non-uniformly sampled map. We confirm the presence of the two horn structure seen by them in CO(2-1) line profile in our data taken in May 1990.

Fig. 8.— As in Fig.2 for R Leo. The lower panel contains line profiles of CO(3-2) line and SiO(8-7) line (left). Map of the emission in the SiO(8-7) line is presented in the middle panel on the right.

### 3.8.   IRC +10216

Maps of this well-known carbon-rich star are presented in Fig.9. In this case we were able to map along with the CO(3-2) emission also emission in the CS(7-6) line. The total integrated flux of CO(3-2) emission is well resolved and has the fitted angular dimension at half maximum of $24'' \times 16''$. The position angle of the major axis is about $100°$. Line profiles toward the star position of both CO(3-2) and CS(7-6) are best fitted with $\gamma \approx 1.6$.

As this star is a subject of detailed study elsewhere (Knapp et al. 1994b), here we want only to point out the clearly visible west-east elongation, present in both lines. The position of peak intensity does not change with velocity. There is also marked asymmetry in the CO(3-2) emission, visible at the level of 20% of maximum flux, namely enhanced emission south of the star position (best visible between –33 and –19 $km\ s^{-1}$).

This star was previously mapped by Troung-Bach, Morris & Nguyen-Q-Rieu (1991), where from maps of the CO(1-0) and CO(2-1) emission they conclude that the observations indicate a spherical symmetry for the envelope.

Fig. 9.— As in Fig.2 for IRC +10216. The lower panel contains line profiles of CO(3-2) line (left) and CS(7-6) line (right). Map of the emission in the CS(7-6) line is presented in the middle panel on the right.

### 3.9. V Hya

Maps of the CO(3-2) emission from this star, obtained using a $9 \times 9$ grid with $9''$ spacing, are presented in Fig.10. The fitted angular extent of the emission at the half maximum of the total integrated flux is $15'' \times 12''$. The position angle of the major axis is about 175°. The CO(3-2) line profile towards the star position is best fitted with high value of $\gamma \approx 20.$, i.e. gaussian-like line shape, although there is present strong red horn enhancement at about 11 $km\ s^{-1}$.

The maps reveal a number of interesting features. The map of the total integrated flux shows very extended emission on the 10% level, unlike the case of other stars we observed when the separations between contours were rather similar. The same map, as well as individual position-velocity maps, shows north-south elongation, confirmed by our fitting procedure. Finally, there is a clearly visible trend in the position of the peak intensities as a function of velocity, with emission from the blue parts of the line being shifted to the west and emission from the red parts of the line being shifted to the east. The amplitude of this effect, indicating a bipolarity in the outflow, is about $3''$.

Fig. 10.— As in Fig.2 for V Hya

This star was previously mapped by Tsuji et al. (1988) and Kahane, Maizels & Jura (1988) in CO(1-0) line and both groups concluded that the emission has a bipolar nature, as confirmed here with better sampled and higher resolution maps of CO(3-2) emission.

### 3.10.  RT Vir

Fig.11 shows $5 \times 5$ maps, made with the $9''$ spacing, of the CO(3-2) emission, which seems to be partially resolved. The total integrated flux map has a fitted angular extent at half maximum of $15'' \times 8''$. The fitted position angle of the major axis is about 30°. CO(3-2) line profile towards the star position is best fitted by slightly flat-topped parabola ($\gamma = 1.3$).

Maps of different parts of the line seems to indicate that the emission is elongated, roughly northeast to southwest. Positions of the peak intensities seems to move slightly with velocity by about $3''$, but in rather incoherent fashion.

### 3.11.  W Hya

Fig. 11.— As in Fig.2 for RT Vir.

$5 \times 5$ maps of the molecular emission from this O-rich star are presented in Fig.12. From the map of the total integrated flux in the CO(3-2) line we get the fitted angular diameter at half maximum of $13'' \times 11''$ at a position angle of $130°$. The CO(3-2) line is best fit with $\gamma = 1.1$, and strong emission in the SiO(8-7) line at 343 GHz is also seen. The CO(3-2) line shows the presence of strong blue horn enhancement, similar to that of U Cam, with a rather weak red horn also present.

The maps of molecular emission shown in Fig.12 reveal the presence of two components. The blue part of the CO(3-2) $(32, 41 \; km \; s^{-1})$ and SiO(8-7) lines are elongated from northeast to southwest, while the red part of CO(3-2) line emission $(41, 51 \; km \; s^{-1})$ is elongated in roughly perpendicular direction, from southeast to northwest. The peak intensity of the redmost part of the CO(3-2) line is shifted by about $5''$ east from otherwise steady peak intensities in other velocity ranges and in the SiO(8-7) line.

### 3.12.   M57

Maps of the molecular emission from the well-known Ring Nebula (M57) are presented on Fig.13. Because of the complicated structure, both grey scale and contour maps of

Fig. 12.— As in Fig.2 for W Hya. The lower panel contains line profiles of CO(3-2) line and SiO(8-7) line (left). Map of the emission in the SiO(8-7) line is presented in the middle panel on the right.

the integrated emission are presented. The emission forms an elliptical ring slightly offset from the center position and with angular dimension at half maximum of $100'' \times 60''$. The position angle of the major axis is about $60°$. No fit was attempted to the line profiles, which often show multiple components. We show the spectrum corresponding to the position of maximum total integrated flux at (–40,–10), and also the average of all the spectra within $\pm 50''$ of the center.

Although the emission from M57 is weak, the maps show a number of remarkable features. First, there is a clearly visible depletion of CO around the central position. Further, the emission shows systematic changes with velocity. The bluemost part of the emission shows concentration towards the central position and comes from the western part of the nebula. Emission from the line center $[-8, 2]$ $km$ $s^{-1}$ comes from outer parts of the nebula. This velocity range shows the presence of two "hot spots", one around (–45,–15) and other one at (+35,+25). Emission coming from the receding part of the nebula is concentrated towards the central position and is visible mostly from the eastern part of the nebula. All maps show a high degree of irregularity.

M57 was observed by Bachiller et al. (1989) in the CO(2-1) and CO(1-0) lines. Our results agree very well with their observations of CO(2-1) emission at $14''$ resolution.

Fig. 13.— As in Fig.2 for M 57. The map of the total integrated flux was in addition presented using greyscale shading (starting at 20% of the maximum) as to clarify complicated spatial structure of this planetary nebula visible in CO emission. The lower panel contains two spectra: spectrum obtained at the offset position (-40,-10), which has the maximum integrated flux (left) and average of all the spectra within the region $\pm 50''$ from the center (right). For M57 no fit to spectral lines was attempted.

Following their suggestions that the observed velocity and spatial structure indicates that the emission is coming from a hollow cylinder ( barrel), inclined with respect to the line of sight, we tried to construct a kinematical model of the nebula. We found that we can reach some agreement when modelling the emission as a thin-walled, elongated cylinder, but we were not able reproduce the observed hot spots within the framework of uniform density and velocity kinematical models.

### 3.13. R Cyg

A map of a $36'' \times 36''$ region around this Mira variable is presented in Fig.14. The $5 \times 5$ sampling grid had a pixel spacing of $9''$. The emission seems to be slightly resolved, with the fitted angular extent at the half maximum of total integrated flux of about $14'' \times 9''$ and

the position angle of 135°, although in this case fit by biaxial gaussian is very approximate. The CO(3-2) line profile towards the central position is best fitted with inverted parabola ($\gamma = 1.9$), although the line shows considerable irregularities.

Fig. 14.— As in Fig.2 for R Cyg.

## 3.14. $\chi$ Cyg

Maps of CO(3-2) emission from this star, obtained using a $7 \times 7$ grid with $10''$ spacing, are presented in Fig.15. The fitted angular extent at the half maximum of the total integrated flux is $16'' \times 10''$. The fitted position angle of the major axis is $115°$. The CO(3-2) line profile towards the star position is best fitted with $\gamma = 1.4$. There is a weak wing present at the red side of the line.

Fig. 15.— As in Fig.2 for $\chi$ Cyg.

The maps show a number of interesting features. First, the emission is clearly extended and elongated from southeast to northwest. Second, there is striking structure present in some velocity-position maps, pointing towards north-west. Finally, peak intensities show bipolarity, with emission shifting towards the west with velocity. The amplitude of this effect is about $4''$.

$\chi$ Cyg was previously mapped by BA in the CO(2-1) line, but they do not find any significant deviations from spherical symmetry.

### 3.15. V Cyg

We mapped V Cyg using a $7 \times 7$ sampling grid with $10''$ spacing, and the resulting maps of molecular emission are presented in Fig.16. From the map of total integrated CO(3-2) emission we get the fitted angular extent at half maximum of $15'' \times 9''$. The position angle of the major axis is $25°$. The spectrum towards the star's position shows CS(7-6) line. The CO(3-2) line profile was best fit with $\gamma = 1.4$. There is a weak wing present at the red part of the line, but we do not integrate emission with $v < 5 \ km \ s^{-1}$ as there is a narrow emission line at about $-1 \ km \ s^{-1}$, probably Galactic in origin, which is strongest to the east from the star.

Fig. 16.— As in Fig.2 for V Cyg. The lower panel contains line profiles of CO(3-2) line and CS(7-6) line (right). Map of the emission in the CS(7-6) line is presented in the middle panel on the right.

The maps of molecular emission are fairly noisy, maps, but there are a number of features we want to comment on. CO(3-2) emission is clearly resolved and shows elongation from northeast to southwest. There is an analogous trend in the position of peak intensities, which move with velocity by about $\pm 3''$, possibly indicating bipolarity of the outflow. CS(7-6) emission is weaker and therefore noisier, but we believe the east-west elongation seen in the middle-right panel is real. Our observations agree with the results of BA (their Fig.10).

## 3.16. CRL 2688

Maps of the molecular emission from this carbon-rich star are presented in Fig.17. From the map of the total integrated CO(3-2) flux we get the fitted diameter of the half maximum emission to be about $12''$. The spectrum taken towards the star's position shows CO(3-2) line and also CS(7-6) emission. The line profile of CO(3-2) emission, discussed by Young et al. (1992), was in the central part best fitted by a gaussian-like shape (Table 2). No fit was attempted to the weaker and noisier CS(7-6) line.

Fig. 17.— As in Fig.2 for CRL 2688. The lower panel contains line profiles of CO(3-2) line and CS(7-6) line (left). Map of the emission in the CS(7-6) line is presented in the middle panel on the right.

The maps show that the emission is basically spherically symmetric, with suggestion of extension toward the north-east. There is possible bipolarity in the positions of the peak intensities, with emission shifting from the east for red parts of the line to the west for blue parts of the line, with an amplitude of about $2''$.

CRL2688 was mapped several times before in different wavelengths and the results were rather inconsistent. The spherical symmetry we observed agrees with the results of observations by Truong-Bach et al. (1990), with somewhat better resolution in the CO(2-1) line, and with the results of Yamamura et al. (1994) obtained with Nobeyama Millimeter Array.

## 3.17. IRC +40540

Maps of the CO(3-2) emission from this star are presented in Fig.18. The total integrated emission seems to be partially resolved and has the fitted angular extent at half maximum of $12'' \times 6''$. The position angle of the major axis is about $60°$. The line profile is best fitted with inverted parabola ($\gamma = 1.9$). There is an enhancement in the line emission at about $18$ $km$ $s^{-1}$.

Fig. 18.— As in Fig.2 for IRC +40540.

Maps of the CO(3-2) emission clearly show that the emission is elongated in the northeast-southwest direction. Individual velocity-position maps show the presence of jet-like structures, the clearest one of which, pointing towards northeast and seen between $-24$ and $-14$ $km$ $s^{-1}$ may be associated with mentioned above enhancement in the line profile. The peak intensities change their position, but in rather incoherent fashion.

## 3.18. R Cas

Maps of the CO(3-2) emission from R Cas, made using a $5 \times 5$ grid with $9''$ spacing, are presented in Fig.19. The half maximum contour of the total integrated flux is elongated

and has fitted angular extent of $13'' \times 10''$. The fitted position angle of the major axis is $70°$. The line profile towards the star position is best fitted with $\gamma = 1.2$, with some red-wing enhancement and weak wind present in the blue part of the line.

Fig. 19.— As in Fig.2 for R Cas.

The maps presented indicate east-west elongation, visible in all individual velocity ranges. The peak intensity of the bluemost part of the CO(3-2) line $(4, 15\ km\ s^{-1})$ is shifted by about $5''$ from otherwise steady peak intensities in other velocity ranges, and also this part of the line shows the clearest elongation.

Molecular emission from this star was previously mapped by BA, but they do not indicate any deviations from spherical symmetry, even if their CO(2-1) map (their Fig.3) seems to suggest some elongation, consistent with what we observed. The multiple horn structure, which they observe in the CO(2-1) line profile, seems to be present also in our observations of the CO(3-2) line, seen in Fig.19.

## 3.19. Discussion

The observations described above show that the majority of the observed stellar envelopes show deviations from circular symmetry when mapped in molecular line emission.

We are reasonably confident that these deviations are real; for example, the derived position angles are randomly distributed. In some cases, our results agree with these of previous observations, but in others they do not. The CO(3-2) line traces higher density gas and is possibly more sensitive to the envelope structure.

## 4. Envelope Radii

CO in molecular outflows is destroyed in the outer parts of stellar envelopes by photodestruction by interstellar ultraviolet radiation, and this process limits the effective sizes of the envelopes as measured by the CO line (Mamon, Glassgold and Huggins 1988). The CO extent of the envelope is given approximately by

$$R_{\rm CO} = 5.4 \times 10^{16} \left( \frac{\dot{M}}{10^{-6}} \right)^{0.65} \left( \frac{V_e}{15} \right)^{-0.55} \left( \frac{f}{8 \times 10^{-4}} \right)^{0.55} + 7.5 \times 10^{15} \left( \frac{V_e}{15} \right) \; cm, \quad (2)$$

where the mass loss rate $\dot{M}$ is in $M_\odot \; yr^{-1}$, $V_e$ is in $km \; s^{-1}$ and $f$, the fractional abundance of CO at the inner edge of the wind is $f = {\rm n(CO)/n(H_2)}$. This interpolation formula is described by Knapp et al. (1994c); the first term is the self-shielding term for CO, and the second is the mean free-flight distance of an unshielded CO molecule before it is destroyed.

The mass loss rates for each of the stars (except M57) were first calculated from the data in Table 2 using the models described by Knapp et al. (1994c), based on earlier work by Knapp & Morris (1985). Table 3 lists for each star the assumed distance in $pc$ (taken from Knapp et al. 1994c) and the mass loss rate. The relative CO abundances were assumed to be $f = 5 \times 10^{-4}$ for oxygen stars, $6.5 \times 10^{-4}$ for S stars and $10^{-3}$ for carbon stars. The effective photodissociation radius was then calculated from this mass loss rate and the wind velocity from Table 2, and is listed in Column 4 of Table 3.

The observed half-power diameters of the stars are listed in the next column. They were calculated using the geometric means of the angular diameters given in the previous section. An upper limit of $10''$ was assumed for any unresolved source. The line emission from circumstellar envelopes is brightest in the center and we have approximated the brightness with a gaussian distribution; we might therefore expect the total source diameter to be about twice as large as the half power diameter, in which case the linear half power diameter should approximately equal the source radius.

As can be seen from Table 3, the agreement between the predicted and observed source radii is generally quite good. The worst discrepancies come from the stars with the largest

Table 3.  Mass Loss Rates and Envelope Sizes

| Star | Distance [$pc$] | $\dot{M}$ [$M_\odot\ yr^{-1}$] | $R_{\mathrm{CO}}$ (mod.) [$10^{16}\ cm$] | $R_{\mathrm{CO}}$ (obs.) [$10^{16}\ cm$] | $R_{\mathrm{dust}}$ [$10^{17}\ cm$] | $M_{\mathrm{env}}$ [$M_\odot$] |
|------|------|------|------|------|------|------|
| R Scl | 330 | $1.8 \times 10^{-6}$ | 9.6 | 8.6 | 19.0 | $7.1 \times 10^{-2}$ |
| o Cet | 80 | $2.6 \times 10^{-7}$ | 3.0 | 1.7 | 1.6 | $1.7 \times 10^{-3}$ |
| U Cam | 430 | $3.5 \times 10^{-6}$ | 12.0 | 9.3 | $\cdots$ | $\cdots$ |
| VY CMa | 1500 | $3.5 \times 10^{-4}$ | 122.0 | 22.0 | $\cdots$ | $\cdots$ |
| OH 231.8+4.2 | 1300 | $3.0 \times 10^{-4}$ | 79.0 | $\leq 30.0$ | $\cdots$ | $\cdots$ |
| RS Cnc | 70 | $6.0 \times 10^{-8}$ | 1.5 | 1.0 | 3.6 | $1.4 \times 10^{-3}$ |
| R Leo | 120 | $1.8 \times 10^{-7}$ | 2.3 | 2.2 | 4.1 | $3.0 \times 10^{-3}$ |
| IRC+10216 | 150 | $2.0 \times 10^{-5}$ | 44.0 | 4.4 | $\cdots$ | $\cdots$ |
| V Hya | 380 | $5.0 \times 10^{-6}$ | 13.0 | 8.0 | $\cdots$ | $\cdots$ |
| RT Vir | 110 | $8.0 \times 10^{-8}$ | 1.5 | 1.8 | 4.1 | $1.2 \times 10^{-3}$ |
| W Hya | 90 | $8.0 \times 10^{-8}$ | 1.5 | 1.6 | 8.5 | $2.5 \times 10^{-3}$ |
| R Cyg | 900 | $3.5 \times 10^{-6}$ | 14.0 | 15.0 | 39.0 | $4.1 \times 10^{-1}$ |
| $\chi$ Cyg | 140 | $2.8 \times 10^{-7}$ | 3.2 | 2.6 | $\cdots$ | $\cdots$ |
| V Cyg | 330 | $9.5 \times 10^{-7}$ | 7.4 | 5.7 | $\cdots$ | $\cdots$ |
| CRL 2688 | 1000 | $2.0 \times 10^{-4}$ | 97.0 | 18.0 | $\cdots$ | $\cdots$ |
| IRC+40540 | 600 | $4.5 \times 10^{-6}$ | 17.0 | 7.6 | $\cdots$ | $\cdots$ |
| R Cas | 160 | $1.0 \times 10^{-6}$ | 5.3 | 2.7 | 6.2 | $1.6 \times 10^{-2}$ |

mass loss rates, such as IRC+10216, CRL 2688 and VY CMa. This observation could indicate that mass loss has not been going on for very long for these stars, but it is more likely that the observations are not sensitive to the weak emission from cold gas at large distances from the star.

The last two columns of Table 3 list the observed angular radius of the dust emission measured from the IRAS data by Young et al. (1993) and the total envelope mass calculated (assuming that the mass loss rate has been constant) from this radius, the outflow speed $V_e$ in Table 2 and the value of the mass loss rate from column 3. It can be seen that, indeed, in all cases the observed CO envelope radius is much smaller than that given by the dust emission, confirming the model of Mamon, Glassgold and Huggins (1988).

## 5. Conclusions

We find that the majority of the observed by us 18 evolved stars show clear deviations from spherical symmetry, in the form of elongated emission, bipolar emission and smaller scale irregularities. This may lead to the conclusion that a substantial fraction of all stars in the AGB phase may lose matter in a non-spherical manner. One needs to look at other mechanisms for distorting the envelope than the action of a binary companion. A promising candidate is convection – there may be only a few convection cells in these enormous stars. One would expect that when the optical photospheres of these stars are resolved the stars themselves will not be spherically symmetric.

Some of the stars we observed are strong enough to be observed in higher than CO(3-2) transitions, which would increase the spatial resolution with which one could map the molecular emission with. Mira (o Ceti) is a strong source, only partially resolved in our data. IRC+10216 is another good candidate. Observations with millimeter wave interferometers would also yield better maps even at lower $J$ transitions. We expect higher resolution maps to reveal the asymmetries we see more clearly.

## REFERENCES

Bachiller, R., Bujarrabal, V., Martin-Pintado, J., & Gómez-González, J., 1989, A&A, 218, 252

Bujarrabal, V., & Alcolea, J. 1991, A&A, 251, 536 (BA)

Cernicharo, J., Guélin, M., Peñalver, J., Martin-Pintado, J. Mauersberger, R. 1989, A&A, 222, L1

Gammie, C. F., Knapp, G. R., Young, K., Phillips, T. G., & Falgarone, E. 1989, ApJ, 345, L87

Kahane, C., Maizels, C., & Jura, M. 1988, ApJ, 328, L25

Knapp, G. R., & Morris, M. 1985, ApJ, 292, 640

Knapp, G. R., Stanek, K. Z., Bowers, P. F., Young, K. & Phillips, T. G. 1994a, in preparation

Knapp, G. R., et al. 1994b, in preparation

Knapp, G. R., Woodhams, M. W., Gammie, C. F., Young, K. & Phillips, T. G. 1994c, in preparation.

Loup, C., Forville, T., Omont, A., & Paul, J. F. 1993, A&AS, 99, 291

Mamon, G. A., Glassgold, A. E., & Huggins, P. J. 1988, ApJ, 328, 797

Morris, M., Guilloteau, S., Lucas, R., & Omont, A. 1987, ApJ, 321, 888

Olofsson, H., Eriksson, K., Gustafsson, B., & Carlström, U. 1993, ApJS, 87, 267

Planesas, P., Bachiller, R., Martin-Pintado, J., & Bujarrabal, V. 1990a, ApJ, 351, 263

Planesas, P., Kenney, J. D., & Bachiller, R. 1990b, ApJ, 364, L9

Truong-Bach, Morris, D., Nguyen-Q-Rieu, & Deguchi, S. 1990, A&A, 230, 431

Truong-Bach, Morris, D., & Nguyen-Q-Rieu 1991, A&A, 249, 435

Tsuji, T., Unno, W., Kaifu, N., Izimura, H., Ukita, N., Cho, S., & Koyama, K. 1988, ApJ, 327, L23

Yamamura, I., Onaka, T., Kamijo, F., Deguchi, S., & Ukita, N., 1994, ApJ, submitted

Young, K., Serabyn, G., Phillips, T. G., Knapp, G. R., Güsten, R., & A. Schulz, 1992, Ap.J. 385, 265

Young, K., Phillips, T. G., & Knapp, G. R. 1993, ApJ Suppl, 86, 517